Pliocene orographic barrier uplift in the southern Central Andes

Heiko Pingel[1], Ricardo N. Alonso[2], Andreas Mulch[3,4], Alexander Rohrmann[1], Masafumi Sudo[1], and Manfred R. Strecker[1]
[1]Institut für Erd- und Umweltwissenschaften, Universität Potsdam, 14476 Potsdam, Germany
[2]Departamento de Geología, Universidad Nacional de Salta, 4400-Salta, Argentina
[3]Institut für Geowissenschaften, Goethe Universität Frankfurt, 60438 Frankfurt/Main, Germany
[4]Biodiversität und Klima Forschungszentrum (BiK-F) and Senckenberg, 60325 Frankfurt/Main, Germany

ABSTRACT

Sedimentary basin fills along the windward flanks of orogenic plateaus are valuable archives of paleoenvironmental change with the potential to resolve the history of surface uplift and orographic barrier formation. The intermontane basins of the southern Central Andes contain thick successions of sedimentary material that are commonly interbedded with datable volcanic ashes. We relate variations in the hydrogen isotopic composition of hydrated volcanic glass (δD_g) of Neogene to Quaternary fills in the semiarid intermontane Humahuaca Basin (Eastern Cordillera, northwest Argentina) to spatiotemporal changes in topography and associated orographic effects. δD values from volcanic glass in the basin strata (–117‰ to –98‰) show two main trends that accompany observed tectonosedimentary events in the study area. Between 6.0 and 3.5 Ma, δD_g values decrease by ~17‰; this is associated with surface uplift in the catchment area. After 3.5 Ma, δD_g values show abrupt deuterium enrichment, which we associate with (1) the attainment of threshold elevations for blocking moisture transport in the basin-bounding ranges to the east, and (2) the onset of semiarid conditions in the basin. Such orographic barriers throughout the eastern flanks of the Central Andes have impeded moisture transport into the orogen interior; this has likely helped maintain aridity and internal drainage conditions on the adjacent Andean Plateau.

INTRODUCTION

Over the past decades, reconstructions of surface uplift of the world's orogenic plateaus have played a pivotal role in assessing the relative importance of mantle dynamics and crustal and/or lithospheric shortening and thickening in shaping the topography of our planet (e.g., Allmendinger et al., 1997; Garzione et al., 2006). However, deconvolving how the complex interactions among surface uplift, atmospheric circulation, and orographic rainfall affect paleoaltimetric reconstructions remains a key challenge for many approaches, including stable isotope studies, which have been among the most prominent methods applied in the Central Andes (e.g., Garzione et al., 2006; 2008; Quade et al., 2007). One promising method to help disentangle the complex tectono-climatic relationships is to focus on the surface-elevation history of plateau bounding margins, because it is challenging to deduce the relative roles of surface uplift and changes in atmospheric patterns from orogen interior stable isotope records alone (e.g., Mulch et al., 2010).

The Andean Altiplano-Puna Plateau is the second largest Cenozoic orogenic plateau on Earth, with an average altitude of 3.7 km, low internal relief, high and deeply incised flanks, and pronounced climatic gradients across the orogen (Fig. 1A; Isacks, 1988). The eastern, windward margin of the plateau has high precipitation and denudation rates that are in contrast to the semiarid to arid conditions and low denudation rates in the orogen interior and along the western plateau margin (Rech et al., 2006; Bookhagen and Strecker, 2008, 2012). Despite extensive stable isotope studies, the timing and style of uplift of the Andean Plateau and its eastern margin (Eastern Cordillera) remain controversial (e.g., Garzione et al., 2006, 2008; Ehlers and Poulsen, 2009; Mulch et al., 2010). However, knowledge of the spatiotemporal development of topography along the eastern Andean flanks is crucial to understand changes in precipitation characteristics over time as well as associated changes in erosion rates and the depositional style of basin fills. In northwestern Argentina and southern Bolivia, the timing of uplift and exhumation has been inferred using low-temperature thermochronology (e.g., Deeken et al., 2006), paleoenvironmental and provenance data obtained from basin fills (e.g., Starck and Anzótegui, 2001; Mazzuoli et al., 2008; Hain et al., 2011; Pingel et al., 2013; Galli et al., 2014), or oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$) isotope data from calcic paleosols (e.g., Mulch et al., 2010). Often, however, precise timing of these events and their regional correlation has been limited by poor chronological constraints.

Here we evaluate topographic growth along the plateau margin using hydrogen isotope ratios of hydrated volcanic glass (δD_g) from the intermontane Humahuaca Basin in northwestern Argentina (Fig. 1). The basin's deformed strata lack continuous sedimentary sections, but they contain abundant datable volcanic ash horizons that provide high-resolution chronologic constraints. We report δD_g values on 17 glass samples from dated volcanic ashes (Table DR1 in the GSA Data Repository[1]) to provide insights into patterns of range uplift and the associated evolution of paleoenvironmental conditions in the southern Central Andes.

GEOLOGICAL SETTING

The Humahuaca Basin is located between 23°S and 24°S in the Eastern Cordillera (Fig. 1). To the west, the Sierra Alta ranges separate the basin from the arid, high-elevation Andean

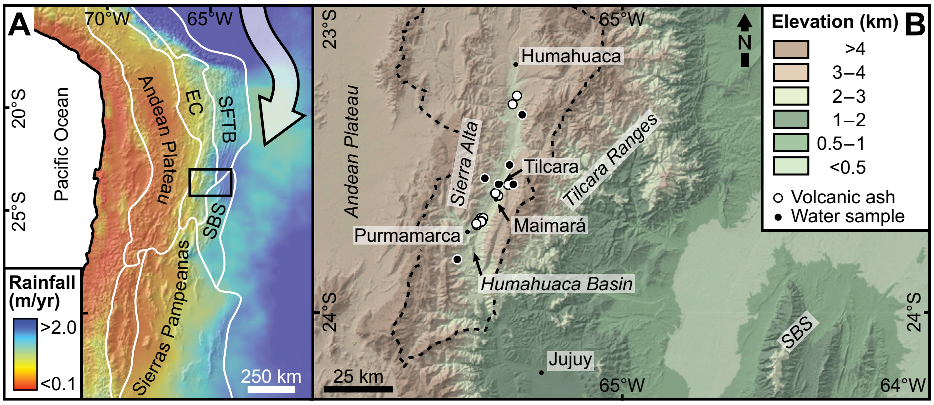

Figure 1. A: Morphotectonic map of southern Central Andes showing mean annual rainfall derived from National Aeronautics and Space Administration Tropical Rainfall Measurement Mission (after Strecker et al., 2007) and main moisture transport (white arrow) to the study area (black box). EC—Eastern Cordillera, SFTB—Subandean fold-thrust belt; SBS—Santa Barbara system. B: Digital elevation model with sample locations of volcanic ashes (white) and modern water (black) in Humahuaca catchment (dashed line).

---

[1]GSA Data Repository item 2014256, stratigraphy, stable isotope analyses of volcanic glass and modern water, and $^{40}Ar/^{39}Ar$ dating, is available online at www.geosociety.org/pubs/ft2014.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

GEOLOGY, August 2014; v. 42; no. 8; p. 691–694; Data Repository item 2014256 | doi:10.1130/G35538.1 | Published online 30 June 2014

Plateau, and to the east, the Tilcara ranges delineate the boundary with the humid sectors of the broken foreland (Santa Barbara system; Figs. 1 and 2D). Thermochronologic and sedimentologic evidence shows that widely distributed deformation within the area that now constitutes the plateau and its present-day eastern margin started in Eocene–Oligocene time (e.g., Deeken et al., 2006; Hongn et al., 2007). During the Miocene–Pliocene, deformation was focused on the Eastern Cordillera and Santa Barbara system, where the formerly contiguous Andean foreland was compartmentalized (e.g., Deeken et al., 2006). While apatite fission-track thermochronology reveals that the Sierra Alta was exhumed rapidly beginning ca. 15–10 Ma (Deeken et al., 2005), Pliocene drainage reorganization within the Humahuaca Basin suggests surface uplift in the Tilcara ranges and foreland fragmentation by ca. 4.2 Ma (Pingel et al., 2013).

The Humahuaca Basin exposes late Miocene–Pliocene sandstones and conglomerates of the Maimará Formation, which unconformably overlie older units. Puna-derived ignimbrite clasts and paleocurrent directions both indicate fluvial connectivity between the orogen interior and the foreland across the present-day basin-bounding ranges (Fig. 2D; Pingel et al., 2013). Interbedded freshwater deposits suggest generally humid conditions at that time (Pingel et al., 2013). While in the south these sedimentary rocks are overlain by the conglomeratic Tilcara Formation (4.2–1.5 Ma; Pingel et al., 2013), the northern part of the basin is characterized by sandstones of the fossiliferous Uquía Formation (ca. 3.5–1.5 Ma; Reguero et al., 2007). Mammal fossil assemblages in the Uquía Formation suggest more humid conditions until ca. 2.5 Ma (Reguero et al., 2007). Axial north-south drainage conditions and the absence of ignimbrite clasts document that the basin-bounding ranges on either side of the basin had attained sufficient elevation to interrupt fluvial connectivity between the plateau, the basin, and the foreland by ca. 4.2 Ma (Pingel et al., 2013). The entire Tertiary sequence is deformed, eroded, and unconformably overlain by multiple generations of thick Quaternary fill units that were episodically deposited and subsequently partly eroded, as a consequence of fluctuations in tectonic activity, climate, and associated local drainage conditions (Tchilinguirian and Pereyra, 2001; Strecker et al., 2007; Pingel et al., 2013).

STABLE ISOTOPE PALEOALTIMETRY AND HYDROGEN ISOTOPE ANALYSIS

Stable isotope paleoaltimetry benefits from a systematic relationship between $\delta^{18}O$ and δD of meteoric water and elevation (e.g., Dansgaard, 1964). Various terrestrial materials incorporate meteoric water by mineral-specific isotope fractionation, preserving a signal of the original isotopic composition of meteoric water. In continental settings, rhyolitic glass may incorporate large amounts of meteoric water (3–8 wt%), saturating ~5–10 k.y. after deposition (Friedman et al., 1993; Mulch et al., 2008; Cassel et al., 2012; Dettinger, 2013). This process occurs systematically, whereby the final δD_g represents an integrated signal of the meteoric water present during hydration that is preserved over geological time scales, allowing for reconstructions of paleoenvironmental conditions (e.g., Friedman et al., 1993; Mulch et al., 2008; Cassel et al., 2012) and to examine feedbacks between tectonic processes and climate (this study).

We analyzed 17 volcanic glass samples from ash beds in late Miocene to Pleistocene sediments of the Humahuaca Basin, from elevations between 2350 m and 2900 m (Fig. 1; Table DR1 in the Data Repository). Our age model relies on new $^{40}Ar/^{39}Ar$ biotite ages, stratigraphic correlation (Fig. DR1), and previously obtained radiometric ages. To compare ancient δD_g with modern meteoric water, we converted δD of 6 stream waters from elevations between 2530 m and 2930 m into glass-hydrogen isotopic composition (Table DR3; Friedman et al., 1993; for details, see the Data Repository).

RESULTS

The δD_g values of all samples range between –98‰ and –117‰ (Table DR1), except for one sample (08HUM03) with an anomalously high δD_g value (–83‰), which was excluded from further interpretation. δD_g values form two distinct trends (Fig. 2A): (1) from 6.0 to 3.5 Ma, average δD_g values decrease by ~17‰, showing high variability, and (2) after 3.5 Ma, δD_g values are significantly higher (–105‰ to –100‰) and relatively stable over time. Present-day stream-water δD values would be in equilibrium with an average δD_{gc} value of –94‰ (Fig. 2A; Table DR3; for details, see the Data Repository).

OROGRAPHIC BARRIER FORMATION AND PLATEAU EXPANSION

There are various potential causes for changes in δD_g values.

1. Although δD of meteoric water is largely coupled to air temperatures during condensation and rainfall, global climate reconstructions show no major cooling trends (e.g., Zachos

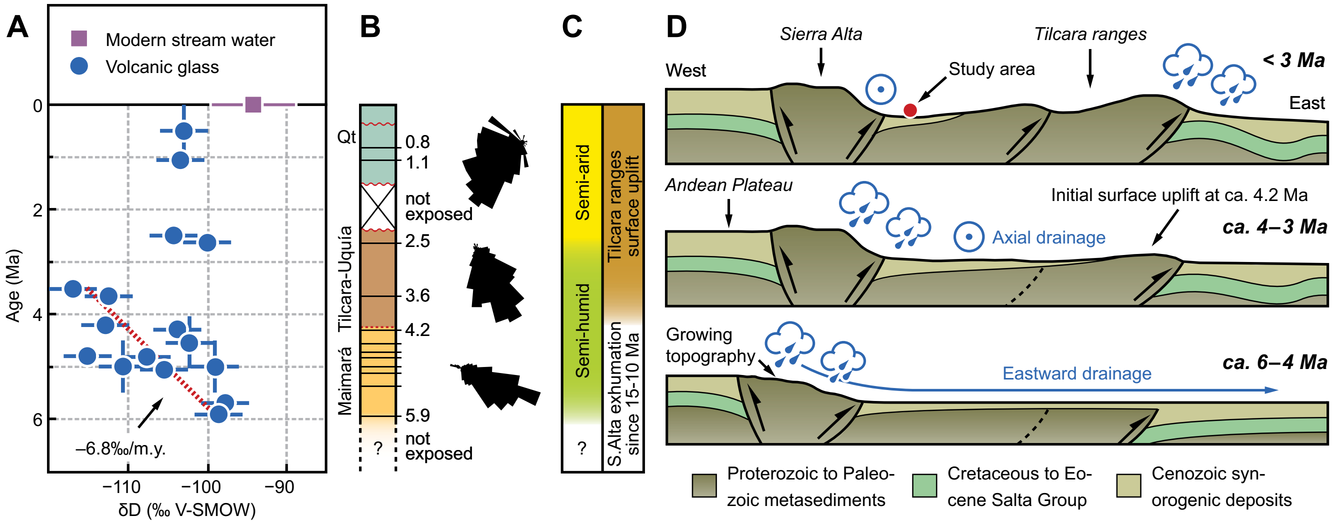

Figure 2. A: δD of volcanic glass (blue circles) and mean modern water (purple square) converted to glass composition (Friedman et al., 1993). Red line depicts mean trend between 6.0 and 3.5 Ma. V-SMOW—Vienna standard mean ocean water. B: Generalized stratigraphy with selected ash layers and age estimates (in Ma; Qt—Quaternary gravels) and paleocurrent estimates from each stratigraphic unit. C: Paleoclimate estimates and uplift history as documented by Pingel et al. (2013). S.—Sierra. D: Conceptual model of basin-and-range development, showing drainage reorganization and shift in orographic rainfall.

et al., 2001) that would explain the initial decrease in δD_g values.

2. An alternative way to lower regional temperatures, and therefore δD values, is to increase elevations, which undoubtedly occurred over the past 6 m.y. (Pingel et al., 2013). The surface uplift that could explain the initial decrease in δD_g can be quantified. However, various assumptions, combined with large uncertainties, may render these estimates insignificant (see the Data Repository).

3. Another possibility is that changing water-vapor sources influenced δD in precipitation. The present-day moisture sources in northwestern Argentina are the Atlantic Ocean and the Amazon Basin (Vera et al., 2006). A shift from the only other potential source in the past (southeast Pacific Ocean) to present-day conditions may have been related to mountain building to the west and likely occurred prior to 10 Ma (Insel et al., 2012). It is therefore unlikely that the moisture source for this sector of the Andes has changed significantly since the late Miocene.

4. The isotopic signature of hydrated glass may be altered by burial heat (Dettinger, 2013); this is an unlikely scenario because the sediment thickness in the study area barely exceeds 1 km.

5. Rainfall amount negatively correlates with δD and $\delta^{18}O$ of precipitation during rainout (Dansgaard, 1964), which becomes relevant when threshold elevations along uplifting mountain ranges are attained (Insel et al., 2012). Because the Sierra Alta underwent deformation by ca. 15–10 Ma, it is likely that the initial decrease in δD_g is in part related to this amount effect.

6. In arid climates D-enriched δD values in hydration water may result from enhanced evaporation either during subcloud evaporation or soil-water formation (e.g., Quade et al., 2007). Our data show a rapid increase in δD_g after ca. 3.5–2.6 Ma (Fig. 2A) that occurs ~0.7–1.6 m.y. after the inferred onset of surface uplift in the present-day Tilcara ranges by 4.2 Ma (Pingel et al., 2013). We suggest that between ca. 3.5 and 2.6 Ma, the Tilcara ranges developed sufficient elevation to force enhanced precipitation along their eastern flanks, which subsequently led to increasingly dry leeward conditions.

In contrast, our modern water isotope data do not show signs of evaporation (Fig. DR3). However, considering that those samples were collected late in the rainy season (March), we do not expect a strong evaporation signal because evaporation and deuterium enrichment are commonly observed during the dry season (Fig. DR6). This may also explain why our δD_{gc} values of modern water (–94‰) are higher than those of Pleistocene glass (–104‰; Fig. 2A), and highlight challenges when comparing stable isotope data from different episodes in the past over which isotopic signals are integrated. Another explanation for this deviation may be related to inherent uncertainties in the empirical glass-fractionation equation (e.g., non–temperature dependent), which, in northwestern Argentina, may result in precisions of ±20‰ (Dettinger, 2013).

Observed trends in our data and the broad synchronicity of isotopic change with tectonosedimentary events in the Humahuaca Basin and the adjacent ranges suggest that changes in isotopic composition are related to topographic growth in the basin catchment. It is intriguing that the temporal discrepancy between initial surface uplift and drainage reorganization recorded in the basin sediments and the isotopic response is likely related to the attainment of threshold elevations in the Tilcara ranges by 4.2 Ma; currently high enough (4–5 km) to intercept easterly moisture-bearing winds and to cause semiarid conditions in the Humahuaca Basin.

These observations have critical implications for the climatic and sedimentary development of the Central Andes and orogenic plateau margins elsewhere. Synchronous with initial surface uplift in the Tilcara ranges at 4.2 Ma, the Sierra Alta gained sufficient elevation to trap sediment sourced in the plateau interior (expansion of the internally drained area; Fig. 2D; Pingel et al., 2013). Moreover, ongoing uplift of the Sierra Alta and the attainment of critical elevations of the Tilcara ranges between 3.5 and 2.6 Ma, associated with increased hinterland aridification and low erosion rates in the lee of the Sierra Alta (e.g., Bookhagen and Strecker, 2012), must have helped to sustain internal drainage conditions on the plateau. Similar observations from other intermontane basins along the Andean plateau margin (e.g., Strecker et al., 2009) support the notion that generally eastward-migrating range uplift forces orographic precipitation toward foreland areas, while the orogen interior increasingly aridifies. In addition, oscillating sedimentary filling and excavation episodes in these marginal basins may have buffered the overall tendency of the fluvial system to incise into the plateau.

Our findings suggest that the efficiency of orographic barriers strongly depends on the development of threshold elevations at which changes in precipitation impact stream power, erosion, and sedimentation due to reduced moisture supply into the orogen interior. As a consequence, such internally-drained, moisture-starved regions are likely to trap large volumes of sediments (e.g., Sobel et al., 2003), ultimately forming extensive low-relief plateaus that may expand as crustal deformation and range uplift propagate outward. Similar positive feedbacks between tectonics and climate may contribute to lateral plateau expansion in the Chinese Qilian Shan or the northern Anatolian plateau.

CONCLUSIONS

We observe a systematic relation between tectonosedimentary events in the Humahuaca Basin and δD of volcanic glass contained in the sedimentary basin fill. Specifically, the initial decrease in δD_g can be related to topographic growth, while hydrogen isotope ratios after ca. 3.5–2.6 Ma likely reflect aridification by orographic barrier formation to the east. These results highlight the potential for isotopic studies of hydrated glass to decipher the history of topography in the Central Andes and other tectonically and volcanically active regions, particularly when threshold elevations for orographic rainfall are attained. We show that in a generally eastward-migrating deformation regime in the southern Central Andes, orographic barriers in the Eastern Cordillera may help maintain internal drainage on the plateau, and that these processes may ultimately favor lateral plateau growth.

ACKNOWLEDGMENTS

This research was funded by Deutsche Forschungsgemeinschaft (DFG) grants STR373/21-1 and 16-1 to Strecker and MU2845/4-1 to Mulch. Mulch acknowledges support through the LOEWE funding program of the Hessen State Ministry of Higher Education, Research, and the Arts. We thank J. Fiebig and U. Treffert (Frankfurt) for laboratory support and T. Schildgen for constructive discussions on an earlier version of the manuscript. We are grateful for comments by E. Cassel and three anonymous reviewers.

REFERENCES CITED

Allmendinger, R.W., Jordan, T.E., Kay, S.M., and Isacks, B.L., 1997, The evolution of the Altiplano-Puna plateau of the Central Andes: Annual Review of Earth and Planetary Sciences, v. 25, p. 139–174, doi:10.1146/annurev.earth.25.1.139.

Bookhagen, B., and Strecker, M.R., 2008, Orographic barriers, high-resolution TRMM rainfall, and relief variations along the eastern Andes: Geophysical Research Letters, v. 35, p. L06403, doi:10.1029/2007GL032011.

Bookhagen, B., and Strecker, M.R., 2012, Spatiotemporal trends in erosion rates across a pronounced rainfall gradient: Examples from the southern Central Andes: Earth and Planetary Science Letters, v. 327–328, p. 97–110, doi:10.1016/j.epsl.2012.02.005.

Cassel, E.J., Graham, S.A., Chamberlain, C.P., and Henry, C.D., 2012, Early Cenozoic topography, morphology, and tectonics of the northern Sierra Nevada and western Basin and Range: Geosphere, v. 8, p. 229–249, doi:10.1130/GES00671.1.

Dansgaard, W., 1964, Stable isotopes in precipitation: Tellus, v. 16, p. 436–468, doi:10.1111/j.2153-3490.1964.tb00181.x.

Deeken, A., Sobel, E.R., Haschke, M., and Riller, U., 2005, Age of initiation and growth pattern of the Puna plateau, NW Argentina, constrained by AFT thermochronology: 19th Colloquium on Latin American Geosciences, Potsdam, Germany: Terra Nostra, v. 05, p. 39.

Deeken, A., Sobel, E.R., Coutand, I., Haschke, M., Riller, U., and Strecker, M.R., 2006, Development of the southern Eastern Cordillera, NW Argentina, constrained by apatite fission track thermochronology: From early Cretaceous extension to middle Miocene shortening: Tectonics, v. 25, doi:10.1029/2005TC001894.

Dettinger, M.P., 2013, Calibrating and testing the volcanic glass paleoaltimeter in South America: [M.S. thesis]: Tucson, University of Arizona, 53 p.

Ehlers, T.A., and Poulsen, C.J., 2009, Influence of Andean uplift on climate and paleoaltimetry estimates: Earth and Planetary Science Letters, v. 281, p. 238–248, doi:10.1016/j.epsl.2009.02.026.

Friedman, I., Gleason, J., Sheppard, R.A., and Gude, A.J., 1993, Deuterium fractionation as water diffuses into silicic volcanic ash, *in* Swart, P.K., et al., eds., Climate change in continental isotopic records: American Geophysical Union Geophysical Monograph 78, p. 321–321, doi:10.1029/GM078p0321.

Galli, C.I., Coira, B., Alonso, R.N., Reynolds, J., Matteini, M., and Hauser, N., 2014, Tectonic controls on the evolution of the Andean Cenozoic foreland basin: Evidence from fluvial system variations in the Payogastilla Group, in the Calchaquí, Tonco and Amblayo Valleys, NW Argentina: Journal of South American Earth Sciences, v. 52, p. 234–259, doi: 10.1016/j.jsames.2014.03.003.

Garzione, C.N., Molnar, P., Libarkin, J., and MacFadden, B., 2006, Rapid late Miocene rise of the Bolivian Altiplano: Evidence for removal of mantle lithosphere: Earth and Planetary Science Letters, v. 241, p. 543–556, doi:10.1016/j.epsl.2005.11.026.

Garzione, C.N., Hoke, G.D., Libarkin, J.C., Withers, S., MacFadden, B., Eiler, J., Ghosh, P., and Mulch, A., 2008, Rise of the Andes: Science, v. 320, p. 1304–1307, doi:10.1126/science.1148615.

Hain, M.P., Strecker, M.R., Bookhagen, B., Alonso, R.N., Pingel, H., and Schmitt, A.K., 2011, Neogene to Quaternary broken foreland formation and sedimentation dynamics in the Andes of NW Argentina (25° S): Tectonics, v. 30, doi:10.1029/2010TC002703.

Hongn, F.D., DelPapa, C., Powell, J., Petrinovic, I., Mon, R., and Deraco, V., 2007, Middle Eocene deformation and sedimentation in the Puna–Eastern Cordillera transition (23°–26°S): Control by preexisting heterogeneities on the pattern of initial Andean shortening: Geology, v. 35, p. 271–274, doi:10.1130/G23189A.1.

Insel, N., Poulsen, C.J., Ehlers, T.A., and Sturm, C., 2012, Response of meteoric δ^{18}O to surface uplift—Implications for Cenozoic Andean Plateau growth: Earth and Planetary Science Letters, v. 317–318, p. 262–272, doi:10.1016/j.epsl.2011.11.039.

Isacks, B.L., 1988, Uplift of the Central Andean Plateau and bending of the Bolivian Orocline: Journal of Geophysical Research, v. 93, p. 3211–3231, doi:10.1029/JB093iB04p03211.

Mazzuoli, R., Vezzoli, L., Omarini, R., Acocella, V., Gioncada, A., Matteini, M., Dini, A., Guillou, H., Hauser, N., and Uttini, A., 2008, Miocene magmatism and tectonics of the easternmost sector of the Calama–Olacapato–El Toro fault system in Central Andes at ~24° S: Insights into the evolution of the Eastern Cordillera: Geological Society of America Bulletin, v. 120, p. 1493–1517, doi: 10.1130/B26109.1.

Mulch, A., Sarna-Wojcicki, A.M., Perkins, M.E., and Chamberlain, C.P., 2008, A Miocene to Pleistocene climate and elevation record of the Sierra Nevada (California): National Academy of Sciences Proceedings, v. 105, p. 6819–6824, doi:10.1073/pnas.0708811105.

Mulch, A., Uba, C.E., Strecker, M.R., Schoenberg, R., and Chamberlain, C.P., 2010, Late Miocene climate variability and surface elevation in the central Andes: Earth and Planetary Science Letters, v. 290, p. 173–182, doi:10.1016/j.epsl.2009.12.019.

Pingel, H., Strecker, M.R., Alonso, R.N., and Schmitt, A.K., 2013, Neotectonic basin and landscape evolution in the Eastern Cordillera of NW Argentina, Humahuaca Basin (~24°S): Basin Research, v. 25, p. 554–573, doi:10.1111/bre.12016.

Quade, J., Garzione, C.N., and Eiler, J., 2007, Paleoelevation reconstruction using pedogenic carbonates: Reviews in Mineralogy and Geochemistry, v. 66, p. 53–87, doi:10.2138/rmg.2007.66.3.

Rech, J.A., Currie, B.S., Michalski, G., and Cowan, A.M., 2006, Neogene climate change and uplift in the Atacama Desert, Chile: Geology, v. 34, p. 761–764, doi:10.1130/G22444.1.

Reguero, M., Candela, A., and Alonso, R.N., 2007, Biochronology and biostratigraphy of the Uquía Formation (Pliocene–early Pleistocene, NW Argentina) and its significance in the Great American Biotic Interchange: Journal of South American Earth Sciences, v. 23, p. 1–16, doi:10.1016/j.jsames.2006.09.005.

Sobel, E.R., Hilley, G.E., and Strecker, M.R., 2003, Formation of internally drained contractional basins by aridity-limited bedrock incision: Journal of Geophysical Research, v. 108, doi:10.1029/2002JB001883.

Starck, D., and Anzótegui, L.M., 2001, The late Miocene climatic change—Persistence of a climatic signal through the orogenic stratigraphic record in northwestern Argentina: Journal of South American Earth Sciences, v. 14, p. 763–774, doi:10.1016/S0895-9811(01)00066-9.

Strecker, M.R., Alonso, R.N., Bookhagen, B., Carrapa, B., Hilley, G.E., Sobel, E.R., and Trauth, M.H., 2007, Tectonics and climate of the southern central Andes: Annual Review of Earth and Planetary Sciences, v. 35, p. 747–787, doi:10.1146/annurev.earth.35.031306.140158.

Strecker, M.R., Alonso, R.N., Bookhagen, B., Carrapa, B., Coutand, I., Hain, M.P., Hilley, G.E., Mortimer, E., Schoenbohm, L., and Sobel, E.R., 2009, Does the topographic distribution of the central Andean Puna Plateau result from climatic or geodynamic processes?: Geology, v. 37, p. 643–646, doi:10.1130/G25545A.1.

Tchilinguirian, P., and Pereyra, F.X., 2001, Geomorfología del sector Salinas Grandes-Quebrada de Humahuaca, provincia de Jujuy: Revista Asociación Geológica Argentina, v. 56, p. 3–15.

Vera, C., Baez, J., Douglas, M., Emmanuel, C.B., Marengo, J., Meitin, J., Nicolini, M., Nogues-Paegle, J., Paegle, J., and Penalba, O., 2006, The South American low-level jet experiment: American Meteorological Society Bulletin, v. 87, p. 63–77, doi:10.1175/BAMS-87-1-63.

Zachos, J., Pagani, M., Sloan, L., Thomas, E., and Billups, K., 2001, Trends, rhythms, and aberrations in global climate 65 Ma to present: Science, v. 292, p. 686–693, doi:10.1126/science.1059412.

Manuscript received 3 February 2014
Revised manuscript received 19 May 2014
Manuscript accepted 27 May 2014

Printed in USA

Downloaded from geology.gsapubs.org on March 31, 2015

Geology

Pliocene orographic barrier uplift in the southern Central Andes

Heiko Pingel, Ricardo N. Alonso, Andreas Mulch, Alexander Rohrmann, Masafumi Sudo and Manfred R. Strecker

Geology 2014;42;691-694
doi: 10.1130/G35538.1

Email alerting services click www.gsapubs.org/cgi/alerts to receive free e-mail alerts when new articles cite this article

Subscribe click www.gsapubs.org/subscriptions/ to subscribe to Geology

Permission request click http://www.geosociety.org/pubs/copyrt.htm#gsa to contact GSA

Copyright not claimed on content prepared wholly by U.S. government employees within scope of their employment. Individual scientists are hereby granted permission, without fees or further requests to GSA, to use a single figure, a single table, and/or a brief paragraph of text in subsequent works and to make unlimited copies of items in GSA's journals for noncommercial use in classrooms to further education and science. This file may not be posted to any Web site, but authors may post the abstracts only of their articles on their own or their organization's Web site providing the posting includes a reference to the article's full citation. GSA provides this and other forums for the presentation of diverse opinions and positions by scientists worldwide, regardless of their race, citizenship, gender, religion, or political viewpoint. Opinions presented in this publication do not reflect official positions of the Society.

Notes

© 2014 Geological Society of America

THE
GEOLOGICAL
SOCIETY
OF AMERICA